

## X-ray variability in M87

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## ABSTRACT

We present the evidence for X-ray variability from the core and from knot A in the M87 jet based on data from two observations with the Einstein Observatory High Resolution Imager (HRI) and three observations with the ROSAT HRI. The core intensity showed a 16% increase in 17 months ('79-'80); a 12% increase in the 3 years '92 to '95; and a 17% drop in the last half of 1995. The intensity of knot A appears to have decreased by 16% between 92Jun and 95Dec. Although the core variability is consistent with general expectations for AGN nuclei, the changes in knot A provide constraints on the x-ray emission process and geometry. Thus we predict that the x-ray morphology of knot A will differ significantly from the radio and optical structure.

Key words: galaxies:active - galaxies:individual:M87 - galaxies:jet - X-rays:galaxies

# 1 INTRODUCTION

The Einstein Observatory (EO) HRI observations of M87 were the first to clearly isolate X-ray emission of the core of the galaxy and of the brightest knot in the jet from the broader distributions known previously (Schreier, Gorenstein & Feigelson 1982). These authors suggested that the core emission was resolved, and thus likely to be thermal bremsstrahlung whereas the emission from knot A was probably synchrotron emission. The EO data were further analyzed by Biretta, Stern & Harris 1991 (hereafter ‘BSH’), who summed the two EO/HRI observations and selected only a portion of the data in order to achieve the best possible image integrity. BSH argued that most of the core emission was unresolved and thus could be similar to nuclear emission from other AGN. Since AGN exhibit X-ray variability with timescales of days to years (e.g. Mushotzky, Done & Pounds 1993), the same behavior could occur in M87.

When the ROSAT archival data became publicly available, it was evident that the intensity ratio of the core to knot A had changed, and we thus proposed further observations with the ROSAT HRI. In this paper we report only on the gross intensity changes since poor aspect solutions (which have an effect similar to ‘pointing jitter’) have degraded the effective resolution of the 1995 data. Consequently, the sizes of the regions used to measure fluxes contain a higher percentage of background emission than desirable. Despite these difficulties, we find convincing evidence for variability in both the core (+ knot D) and in knot A (+ knot B).

The most reliable evidence for variability comes from a comparison between the multiple observations made with each satellite. When comparing Einstein and ROSAT data however, the difference in effective area as a function of energy between the two satellites introduces an uncertainty because we have no knowledge of the X-ray spectral distributions of the various components.

## 2 DATA REDUCTION

### 2.1 The data

The observations used in this paper are summarized in Table 1. The ROSAT images are shown in Figure 1, and may be compared to Figures 1 and 2 of BSH. It is apparent that the 1995 data suffer from severe aspect smearing and that the intensity ratio of the core to knot A has increased. The degradation in resolution from the aspect problem is not easily fixed. The only other source in the field with a reasonable intensity is too far off axis ( $12.2'$ ) to serve as a template for a point response function.

### 2.2 Selection of regions for measuring the intensities

To derive reliable intensities, we need to ensure that we collect the same fraction of source counts for each feature and each observation. Poor aspect degrades the resolution. N/S profiles on the maps smoothed with a  $3''$  Gaussian give FWHMs of  $7.5''$  for the core and  $7.2''$  for knot A in the 92Jun data, but  $10.0''$  for both features in the 95Jun data. Therefore, small radii circles would not measure the same fraction of counts for different observations.

Although larger integration areas can overcome the aspect smearing, they will suffer from greater contamination with (non-variable) background emission. Moreover, the core and knot A are separated by only  $12''$ . Consequently, we have made two sets of intensity measurements: one by selecting adjoining boxes, and the other with circular apertures of radius,  $r=6''$ . The former will be used for comparing countrates but will underestimate any variability because of contamination by extended, non-variable emission. The latter method should be more reliable for measuring the ratio of the core to knot A (assuming the aspect smearing affects both components equally), but cannot be used for comparing countrates for a given feature from different observations.

For the ‘adjoining rectangle’ method, we chose in each map the same central reference point lying on the line joining the two peaks, at about the location of the saddle point in X-ray brightness between the core and knot A. This reference point was derived from the  $3''$  smoothed contour plots. Using a rotation of  $20^\circ$ , two adjoining boxes of dimensions  $\Delta x' = 16''$ ,  $\Delta y' = 26''$  were constructed. (The primed coordinates refer to the rotated frame.) For the background, we joined the two measuring boxes to make the sum ( $32'' \times 26''$ ) and used a  $10''$  border around this box (all centered on the reference point). We also use this same background frame for the  $r=6''$  circular aperture. A rough sketch of this geometry is shown in Figure 2.

For each map, positions of the core and knot A were determined by the detection algorithm in IRAF/PROS and checked with contour diagrams of the smoothed images (Fig. 1). For the circular apertures, these positions defined the centers of the circles. The two Einstein observations were reduced in the same manner as the ROSAT data.

## 3 VARIABILITY OF THE CORE AND KNOT A

### 3.1 Ratio of core to knot A

The observable which is least affected by systematic differences between EO and ROSAT, and between differences in quality of aspect solutions, is the ratio of the flux of the core to knot A. While there will always be some degree of ‘contamination’ in the measuring circles because the background is estimated within a region somewhat removed from the core and knot A, this effect is minimized by using the small area of the circular apertures. We also expect that whatever loss occurs from aspect smearing will affect both core and knot A equally, so such an effect will only serve to reduce any real changes in the ratio.

The only important uncertainty which we have identified is the difference in the effective areas of EO and ROSAT. If the core were significantly harder than knot A, then EO would find a different ratio for the core to knot A than would ROSAT, supposing that they observed the source at the same time. The unknown spectral distributions of the core and knot A lead to an uncertainty of roughly  $\pm 25\%$  (for a reasonable range of spectral distributions, see below) when comparing EO with ROSAT countrates. The results for the circular apertures and ratios are given in Table 2 and plotted in Figure 3a.

### 3.2 Countrates for the core and knot A

While the HRI on Einstein was very similar to that on ROSAT, the quantum efficiency and effective area were much smaller and the energy band was wider. Both the PIMMS software (a multi-mission tool distributed by the High Energy Astrophysics Science Archive Research Center, Goddard Space Flight Center) and the 'xflux' task in IRAF/PROS use the appropriate effective areas of mirror/detector pairs, and allow convolution with simple spectral shapes. The conversion factor,  $C$ , ( $\text{ROSAT c/s} = C \times \text{EO c/s}$ ) for a power law spectrum with energy index  $\alpha = 1.3$  [ $S \propto \nu^{-\alpha}$ ] and column density,  $\log N_H = 20.38$  (the values used in BSH), is 1.75 for PIMMS and 2.05 for xflux. These numbers may be compared to conversion factors deduced from Table 4 of the HRI Calibration Report (David et al. 1995) for various supernova remnants where the conversion factors are generally greater than 3. In view of this uncertainty, we have chosen to use the M87 cluster gas itself as our primary intensity calibrator. To do this, we measured the countrate in a circle of radius  $276''$  centered on the reference point described above. For the background, we used an annulus with radii of  $280''$  and  $300''$ . We excluded from the circle the inner box ( $32'' \times 26''$ , rotated by  $20^\circ$ ) which contains the core and knot A. The correction factors necessary to obtain the 95Jun value (which is taken as the fiducial point) are listed in Table 3. They may be compared with results for bremsstrahlung spectra with  $kT = 2$  keV and  $\log N_H = 20.38$  of 2.1 for PIMMS and 2.45 for xflux.

As discussed above, we have based our countrate estimates on intensity measurements in  $16'' \times 26''$  boxes. The countrates for the core and knot A from both instruments are given in Table 4 and plotted in Figure 3b. The chief uncertainty is the correction factor used to convert Einstein countrates to ROSAT values. This factor is derived from the countrates of the cluster gas which is believed to have a temperature close to 2 keV (Fabricant, Lecar & Gorenstein 1980; Nulsen & Böhringer, 1995). Consequently, the conversion factor could be as much as 35% smaller if the spectral distribution of the core or knot A were to be extremely different from that of the cluster gas. This spectral uncertainty precludes a definitive statement about the history of the variability on the 10 year time scale covered by the Einstein and ROSAT observations. However, the Einstein data alone show that the core intensity increased by 16% ( $4\sigma$ ) between 79Dec and 80Jul whereas knot A increased by less than 7% during the same period ( $1.5\sigma$ ). During the 3.5 year ROSAT coverage, knot A declined by 16% and the core increased by 12% ( $3\sigma$ ) from 92Jun to 95Jun and declined by 17% ( $7\sigma$ ) in the following 6 months.

We also searched for short time-scale variability during each ROSAT observation (one to three days of length). Kolmogorov-Smirnov and Cramer-von Mises one-sample goodness-of-fit tests were performed using the circular apertures for both the core and knot A in order to test the null hypothesis of constant source intensity. The only instance where the statistic exceeded 99% was for knot A, 95Jun. The light curve shows a 20% enhancement for about 12 hours on 95Jun09. This behavior could be caused by aspect problems, and will be investigated at a later time.

## 4 DISCUSSION

The magnitude of the characteristic changes is of order  $0.02 \text{ count s}^{-1}$ . The conversion of ROSAT countrate to luminosity at M87 (assumed to be 16 Mpc distant) varies between  $3 \times 10^{41} \text{ erg/count}$  for soft spectral distributions (power laws with  $\alpha = 2.5$  or bremsstrahlung spectra with  $kT = 0.2 \text{ keV}$ ) to  $14 \times 10^{41} \text{ erg/count}$  for harder spectra ( $\alpha = 0.2$  or  $kT = 10 \text{ keV}$ ). Consequently, the changes we have observed are of order  $\Delta L_x(0.5\text{-}3\text{keV}) = 10^{40} \text{ erg/s}$ ; substantially larger than the typical luminosities of galactic binaries (Tanaka & Lewin 1995; van Paradijs & McClintock 1995).

Conventional explanations for the X-ray emission from the cores of galaxies containing massive black holes are either thermal emission from the putative accretion disk or non-thermal emission, possibly associated with the inner jet, which may be strongly beamed. Either of these models can easily accommodate the observed variability and short timescales. Additionally, larger fractional changes have been observed for other AGN (e.g. the Seyfert I galaxies reported by Boller, Brandt & Fink 1996). Rapid variations have also been seen in VLBI observations of the nucleus. Junor & Biretta (1995) have found evidence for changes in the jet structure in 1.3 cm VLBI images on very small scales ( $\approx 0.01 \text{ pc}$ ) accompanied by a decrease in the core brightness of  $\approx 30\%$  over 5 months in 1992. In 1977, a ‘flare’ was observed with 2.3 GHz VLBI; the amplitude changed by 30% over 4 months (Morabito, Preston & Jauncey 1988). While there are no simultaneous flux measurements in the radio or optical bands, the sporadic data which are available show the same sort of behavior as that in Figure 3b. The 2 cm radio core flux density ( $0.15''$  resolution) increased by 13% between 93Jan and 94May. (These VLA data are described in Biretta, Zhou & Owen (1995).) The ultraviolet flux from the core ( $0.04''$  resolution) decreased by a similar amount between 94Aug and 95Jul (Biretta, Sparks & Macchetto 1996). These data are consistent with a maximum in the core’s lightcurve occurring in mid 1994.

For knot A, the situation is different. Even if the apparent decrease of more than 10% between 1980 and 1992 is uncertain because the spectral distribution is unknown, the secular dimming of 16% between 1992Jun and 1995Dec is a  $3\sigma$  effect. The observed decline (of order 4%/yr) is consistent with the halflife (12.8 yr) estimated by BSH for relativistic electrons producing X-ray synchrotron emission in a  $200\mu\text{G}$  field. However, the physical size of knot A is known from radio and optical data to be of order 70 parsec by a few parsecs (i.e. a thin shock disk). Therefore, the observed decrease could be explained by (a) 100% variability from a region of order a light year across which, at maximum, contributes about 20% of the knot A flux; (b) the entire X-ray emitting volume of knot A could be substantially smaller than the diameter of the disk which produces the optical and radio emission; or (c) relativistic effects such as a change of a beaming angle might be present. For the former cases, the time scale of the observed decrease favors synchrotron emission as the X-ray emission process. BSH estimate cooling times for thermal models of over 100,000 years, and inverse Compton models always involve relativistic electrons with substantially lower energies (and hence longer lifetimes) than those required to produce X-ray synchrotron emission. Additional ROSAT observations have been approved to monitor M87 at 6 month intervals and contemporary optical and radio observations are planned.

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Table 1 Observations

Date	Seq #	Livetime (secs)	Comments
1979Jul05	H282	72662	See BSH for details
1980Dec09	H10316	49249	See BSH for details
1992Jun07	wh700214	13954	good aspect
1995Jun09	us701712	44264	poor aspect
1995Dec16	us701713	40362	poor aspect

Notes: Deadtimes for Einstein are assumed to be 4%; for ROSAT they are 2%.

Table 2 Circular Aperture Counts for the Ratio of Core / Knot A

	1979	1980	1992Jun	1995Jun	1995Dec
core raw	2185	1535	1281	4465	3267
core net	1842 (48)	1325 (40)	1084 (37)	3843 (68)	2702 (58)
knot A raw	2082	1383	1022	2892	2578
knot A net	1742 (47)	1174 (38)	826 (33)	2271 (55)	2012 (52)
ratio (net)	1.06 (.04)	1.13 (.05)	1.31 (.07)	1.69 (.05)	1.34 (.05)

Note:  $1\sigma$  errors are given in parentheses; those on the ratios are the sums of the errors on each component, taken in quadrature. The Einstein ratios may be compared to that derived in the BSH paper where extensive image processing was performed so that background contamination was minimized:  $(\text{Core} + \text{knot D}) / (\text{knot A} + \text{knot B}) = 1.15$

Table 3 Intensity Calibration Based on Extended Thermal Emission

Date	Raw (cnts)	Net countrate (c/s)	CorFac to 95Jun
79Jul	124324	0.780 (0.010)	2.940 (1.3%)
80Dec	72388	0.671 (0.012)	3.418 (1.8%)
92Jun	57660	2.183 (0.034)	1.050 (1.6%)
95Jun	185689	2.293 (0.019)	1.000 (0.8%)
95Dec	167682	2.304 (0.020)	0.995 (0.9%)

Note: Raw counts are the value for the  $r = 276''$  circle centered on the reference point, minus the counts in the rotated box ( $32'' \times 26''$ ). The net countrate is based on the background subtraction of the  $280''$  to  $300''$  annulus. The 5% difference between 92Jun and 95Jun is ascribed to the change in high voltage (94Jun; see the HRI Calibration Report, David et al. 1995). The 16% difference between the two Einstein observations is reasonably close to the 12.3% drop in sensitivity expected in the 17 months between the two observations. This secular change in the sensitivity is scaled from the estimate of 8.7%/yr derived from observations of a number of supernova remnants and Abell 496 (Seward and Martenis, internal Einstein Memo of 1988 Jul 21).  $1 \sigma$  errors are given in parentheses.

Table 4 Core and Knot A Countrates

Date	CORE		KNOT A	
	Box (cnts)	Net countrate (c/ksec)	Box (cnts)	Net countrate (c/ksec)
79Jul	4133	116.5 (2.8)	3680	98.0 (2.6)
80Dec	2722	135.5 (3.8)	2275	104.5 (3.5)
92Jun	2336	123.7 (3.9)	1873	88.4 (3.5)
95Jun	8417	138.6 (2.2)	5782	79.0 (1.8)
95Dec	6747	115.1 (2.1)	5104	74.5 (1.9)

Note: the box counts (columns 2 and 4) are given without any corrections but the countrates (columns 3 and 5) are corrected for background in the  $10''$  wide frame and have been multiplied by the appropriate correction factor from Table 3.  $1 \sigma$  errors are given in parentheses.



Figure 1: Contour diagrams of the data with a  $3''$  FWHM Gaussian smoothing function. The maps have been scaled by  $10^6/\text{lifetime}$  to change the units to counts/pixel/Megasec. The pixel size is  $0.5''$  and the contour levels are logarithmic: 40, 53, 70, 93, 124, 164, 218, and 290 c/pix/Ms. (a) 1992Jun; (b) 1995Jun; (c) 1995Dec.

Figure 2: A grey scale image of M87 with the approximate geometry for intensity measurements shown. The inner rectangle is divided into 2 equal areas for the ‘adjoining rectangle’ method discussed in the text.

### Figure 3: Variability Results

For calendar dates, see Table 1. (a) the ratio of net counts in  $r = 6''$  circular apertures centered on the core and knot A. (b) the countrates (c/ksec) for the box measurements of the core (circles) and knot A (squares). The correction factors used are those from Table 3. Included as a control (the x’s) are the differences between the countrates in the background frame and the countrates in a circle ( $r = 12''$ ) located  $45''$  to the SE of the reference point (a region where the X-ray surface brightness is without large spatial gradients and is approximately 60% of the average frame value).

For the Einstein data, additional uncertainties caused by the unknown spectral distribution of components, are roughly +6% (for harder spectra, up to 10 keV, or  $\alpha$  down to 0.3) and –35% (for softer spectra, down to 0.3 keV or  $\alpha$  up to 2.4). Similar uncertainties would apply to the ROSAT data only if the variability was accompanied by a significant change in spectral distribution.











